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13. ABSTRACT (Maximum 200 words)

The boundary layer in electrothermal-chemical devices plays a major role in burn process at the plasma-propellant interface. The set of experiments conducted at NC State University on JA-2 solid granular propellant showed evidence of enhanced burn rates when the plasma is injected normal to the grains. for the tested range of pressure between 55 and 90 MPa (8,000 and 12,000 psi, respectively) over 400 μs pulse length. Results showed a geometry influence on the burn rates when plasma is injected at an inclination angle to the surface of the propellant. Calculations were performed using SODIN code and compared to values obtained from optical emission spectroscopy. Core and boundary layer plasma temperatures are about 1.7 and 0.8 eV, respectively. The heat flux at the boundary layer is about 10% of that of the source, suggesting that the plasma energy deposited on the propellant is mostly absorbed in the boundary layer. The obtained value of the energy transmission factor ($f \approx 10\%$) suggests that radiative heating may be limited during the burn of the propellant due to limited energy transport to the surface, and that plasma kinetic pressure has a stronger effect on the burn rate than the plasma radiative heat flux.



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## Progress Report

## July 1, 1996

# AUGMENTATION AND CONTROL OF BURN RATE IN PLASMA-DEVICES

**(Contract N00014-95-1-1221, R&D Number 33e1016---01)**
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The understanding of the boundary layer physics is essential for a possible control of the performance of electrothermal-chemical devices. A plasma source performance depends on how the plasma is generated and then expands into the combustion chamber, and how plasma temperature and pressure affects the burn rates of candidate propellants. The interior ballistics are highly affected by the micro-processes within the boundary layer. In any ETC device, the boundary layer is more complex due to plasma-propellant mixing during the burn and combustion processes. Our approach focuses on:

- Boundary layer physics in electrothermal-chemical devices.
- Experiments and modeling of plasma flow and flame-vapor shield.
- Plasma-propellant and plasma-bore interface, and experimental verification of vapor shield effect.
- Development of useful diagnostics for core and plasma boundary.
- Physics of plasma-propellant interaction and experiments on burn rates of various propellants.
- Geometrical influence on burn rates of solid granular propellants.
- Decoupling plasma parameters and effect of individual properties on burn rates.

During this reporting period, we report on the progress in plasma-propellant interaction and investigation of the boundary layer behavior at the plasma-propellant interface. We focus on the effectiveness of radiative heating on the burn rates of JA-2 solid propellant to evaluate the role of radiative heating versus plasma kinetic pressure effects.

Following our 1995 End-of-Fiscal-Year report, where we reported on a set of experiments to evaluate burn rates of JA-2 solid propellant, an analysis of the experimental shots conducted on JA2 solid propellant as a function of plasma injection angle has been fulfilled. This analysis compares the experimentally measured plasma temperature, density and pressure to the code predicted values. The 1-D, time dependent code SODIN has been used to predict the plasma parameters of the source for the shots when the plasma is injected into the propellant surface at different inclination angles. The experimental values of the plasma parameters, temperature and density, were obtained from optical emission spectroscopy measurements. Because of the fact that the plasma is optically thick, the optical emission spectroscopy data are indicative of the plasma boundary layer, and hence, obtained parameters are those for the boundary layer.

Time-averaged boundary layer temperatures of 8,800 to 14,000 $^{o}$K ($\approx$ 0.8 - 1.2 eV) and plasma densities of $2 \times 10^{23}$ to $4.5 \times 10^{23}$ $m^{-3}$ have been deduced by measurements along the axis of the device using the relative intensities and the Stark broadening of the copper lines. Comparisons with the measured burn rates of the JA-2 propellant versus the inclination angle suggests a stronger correlation of plasma burn rate with plasma kinetic pressure than with the radiative heat flux. Estimates of the temperatures and densities for some shots were analyzed by observing the $C_2$ Swan Bands. The data were compared with synthetic spectra calculated using the UVCODE molecular spectra-radiative transport code.

The plasma temperature calculated using a Boltzmann plot of neutral copper lines correlates well to that obtained from $CO_2$ emission predictions with the data. The plasma density calculated from the Stark broadening of neutral copper lines correlates also well to that obtained from $CO_2$ emission predictions with data. Both plasma temperature and density decrease with increased angles of injection.

The plasma pressure and the source heat flux are calculated by SODIN code for the same shots. SODIN code calculates the plasma parameters using the discharge current data file as an input to the code, and solves the set of governing equations self consistently. The average pressure for these shots is about 125±25 MPa, peak plasma pressure is 250±50 MPa, and source heat flux is 28±6 $GW/m^2$. The values calculated by the code are those at the source exit (last node in the source), and are typical and consistent for shots at 5 kJ input energy to the source.

The core plasma temperature, as predicted by SODIN Code, is compared to the plasma boundary layer temperature calculated from optical emission spectroscopy. The average core plasma temperature is about 1.7±0.1 eV, while the plasma boundary layer temperature varies from 1.24 eV at $0^o$ to 0.8 eV at $90^o$. In fact, the average plasma boundary layer temperature has an average of 0.88±0.1 eV over the entire range of injection angle except at $0^o$ where it has a higher value (1.24 eV). The difference between temperatures (core and boundary) suggests that the boundary layer plays a role in absorbing a substantial fraction of the incoming heat flux (vapor shield mechanism), which is typical for ablating surfaces under high heat flux irradiation. This vapor shield mechanism would then reduce the effectiveness of radiative heating on the propellant. In order to estimate the effectiveness of the vapor shield, the core and boundary layer plasmas are both assumed to radiate as a blackbody such that the heat flux of the source and the boundary are scaled to the temperature by Stephen-Boltzmann's law. The source fluence may be expressed as:

$$q''_{(source)} = \sigma (T_{SODIN})^4$$

where $T_{SODIN}$ is the core plasma temperature at the source exit, and $\sigma$ is the Stephen-Boltzmann's constant. The heat flux at the boundary layer is given by:

$$q''_{(boundary)} = f \, \sigma (T_{boundary})^4$$

where $T_{boundary}$ is the boundary layer temperature as calculated from spectroscopy measurements, and $f$ is the energy transmission factor through the vapor shield layer. An estimate of the energy transmission factor can be obtained from the ratio between the boundary layer heat flux to the source flounce:

$$f = q''_{(boundary)} / q''_{(source)}$$

The energy transmission factor is about 10% and less for angles between 15 and 90°, which is also expected for most ablating surfaces when a vapor shield layer is developed and reaches steady-state. The highest value obtained for the factor $f$ is 35% at 0°, which correlates to results observed for most graphite surfaces at such inclination angle. The obtained values of the factor $f$ suggest that radiative heating may be limited during the burn of the propellant due to limited energy transport to the surface, and that plasma kinetic pressure has a stronger effect on the burn rate than the plasma radiative heat flux.

Our research continues to further understand the role of radiative heating versus pressure effects, and whether the burn rate is highly dependent on radiative heating, plasma kinetic pressure, or both. Additionally, a set of decoupling experiments will be conducted to isolate several possible mechanisms in order to understand each mechanism individually. Modeling is ongoing and our 2-D boundary layer model is near completion, which includes turbulent flow and radiation transport.

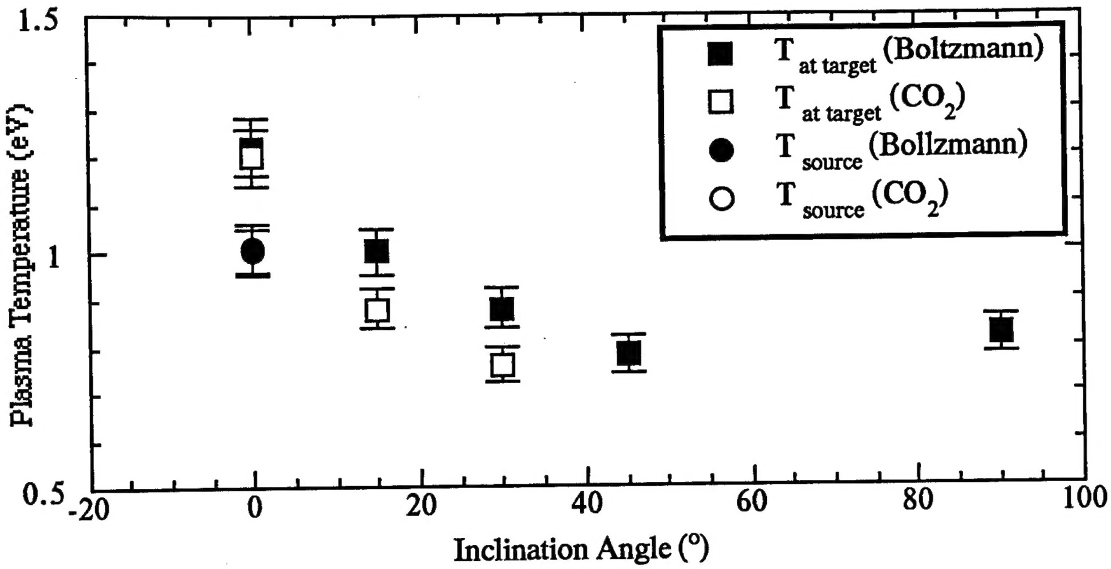


Fig. 1 Plasma temperature calculated using a Boltzmann plot of neutral copper lines and a match of $CO_2$ emission predictions with the data.

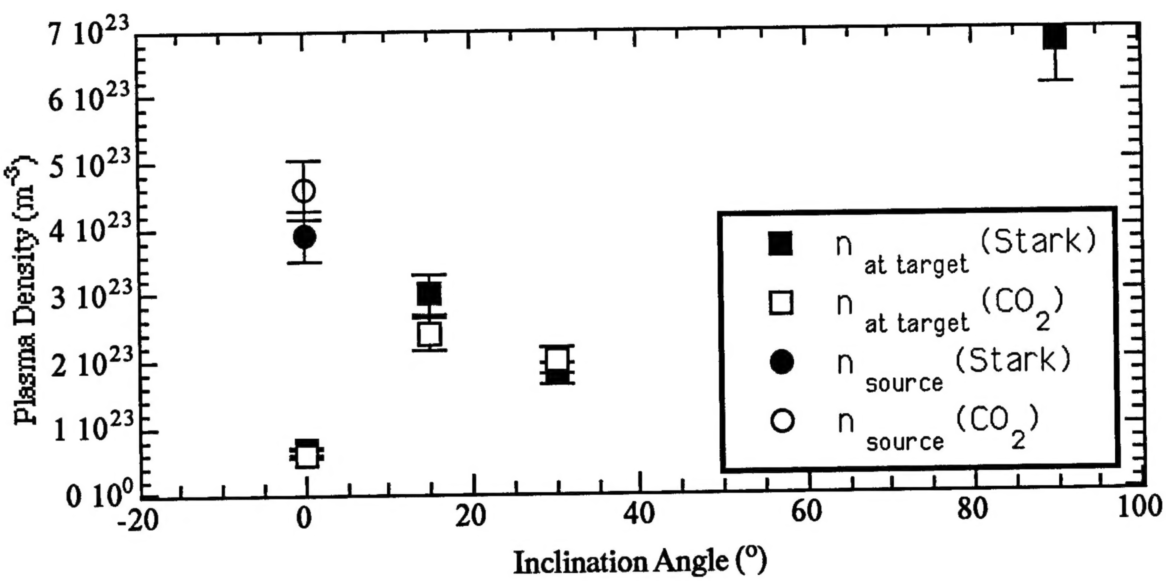


Fig. 2 Plasma density calculated from the Stark broadening of neutral copper lines and matching $CO_2$ emission predictions with data.

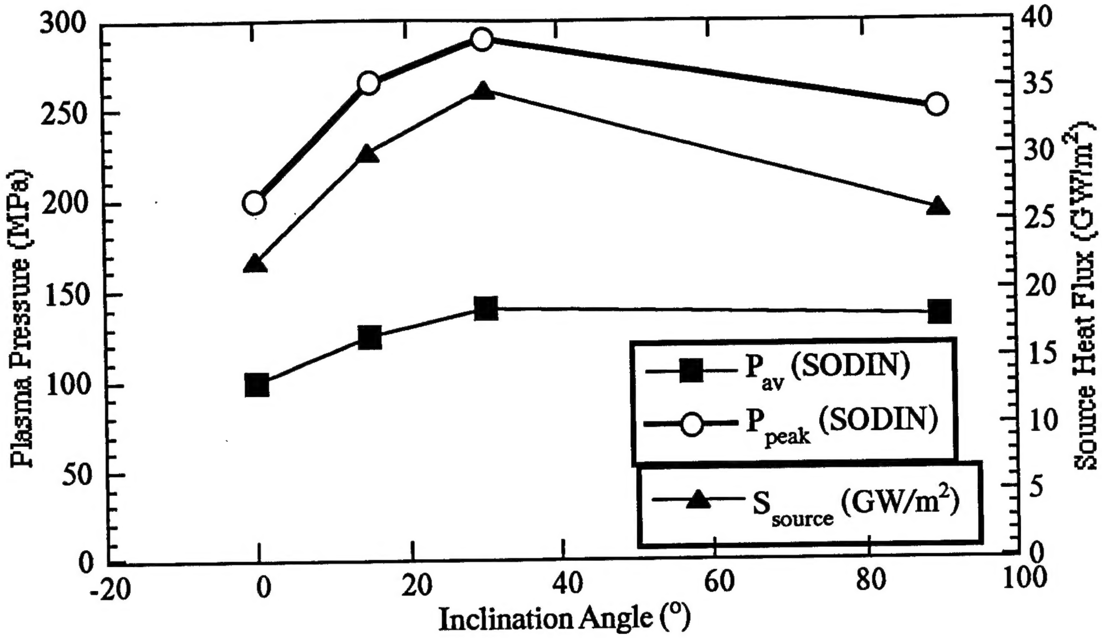


Fig. 3 Plasma pressure (peak and average) and source heat flux as predicted by SODIN Code for shots taken at different angle of inclination.

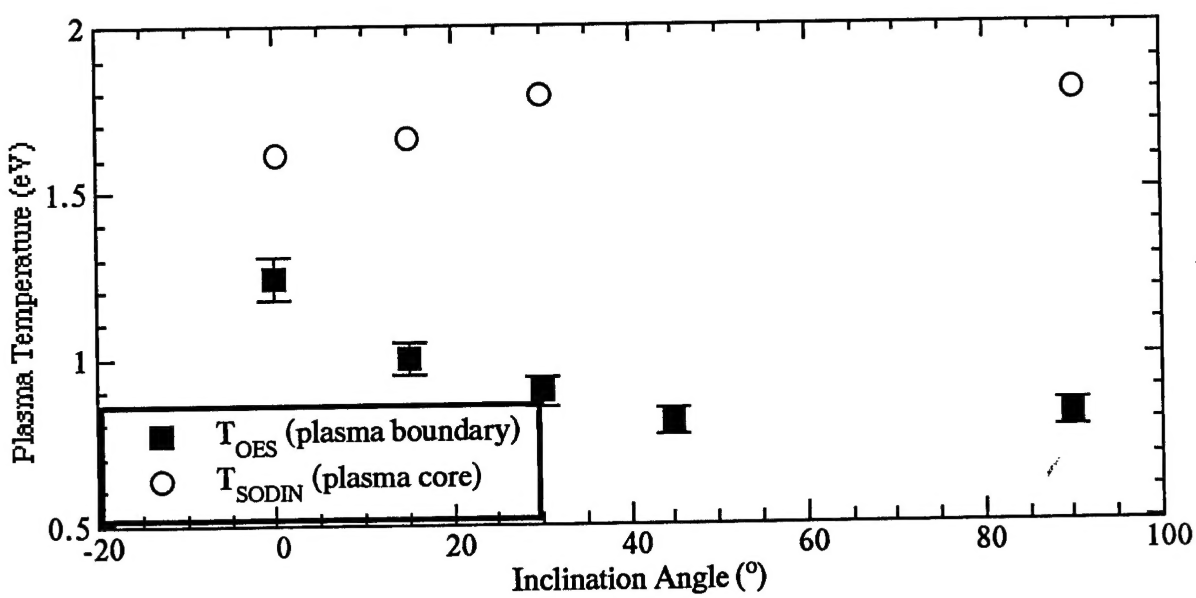


Fig. 4 Plasma temperature (core plasma) as predicted by SODIN Code compared to that calculated from Optical Emission Spectroscopy (plasma boundary).

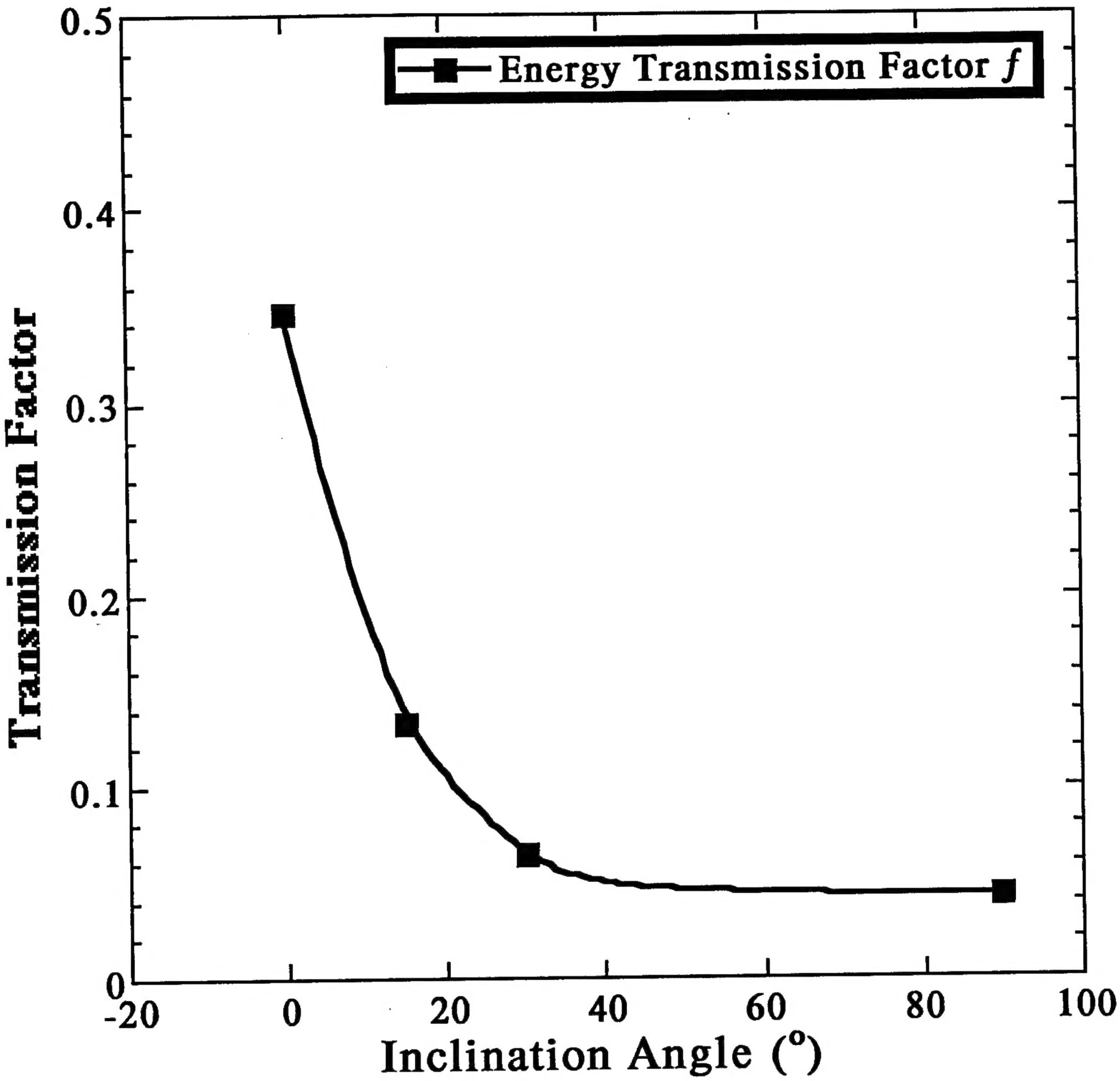


Fig. 5 Energy transmission factor $f$ through the developed vapor layer (plasma boundary layer) calculated from the ration between the surface heat flux (at the boundary) and the core plasma heat fluence.

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